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# Driving and charging patterns of electric vehicles for energy usage

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ABSTRACT

This paper presents findings from the Western Australian Electric Vehicle Trial (2010–2012) and the ongoing Electric vehicle (EV) charging research network in Perth. The University of Western Australia is collecting the data from eleven locally converted EVs and 23 charging stations. The data confirms most charging is conducted at business and home locations (55%), while charging stations were only used for 33% of charging events. The EV charging power over time-of-day and aggregated over all charging stations closely resembles a solar PV curve, which means that EV charging stations can ideally be offset by solar PV. Another important finding is that EVs spend significantly more time at a charging station than what is technically required for the charging process. Also on average, EVs have more than 50% battery charge remaining when they plug in. This tells us parking spaces are in higher demand than Level-2 charging facilities.



**Contents**



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## 1. Introduction

Rising fuel costs, growing public awareness and concern over environmental issues such as urban air quality and global warming, combined with higher-performance batteries mean that electric vehicles are emerging as an attractive alternative to internal combustion engine (ICE) petrol/diesel vehicles. Automobile manufacturers such as Nissan, Mitsubishi, BMW, Renault, Ford and Tesla are taking advantage of the emerging marketplace by releasing their own commercial electric vehicles. EVs can be home charged, so they do not require an immediate charging infrastructure, however it can be argued that EV take-up rates do depend on the availability of an adequate EV charging infrastructure. Modern charging stations can adapt their energy usage to grid load requirements by reducing or increasing charge current. This also allows charging stations to maximise renewable energy usage, e.g. through charging with higher currents during sunshine hours or during times of high wind speeds and low energy demand at night. Careful analysis, planning and management will be needed to determine the necessity, reduce the costs of, and optimise placement and operation of this charging infrastructure.

In this paper we analyse and discuss the data that has been collected from eleven EVs and 23 charging stations during the WA Electric Vehicle Trial (January 2010–December 2012), the first electric vehicle trial conducted in Australia (Fig. 1). The data collected shows for each charging event the energy used and the start and stop time of charging. This can be used to determine a possible renewable energy offset and to predict the impact of a future larger fleet of EVs on the power distribution network. All trial EVs were equipped with black box data loggers, so we received charging events not only from charging stations, but also from all other locations where a car has been plugged in, most notably home and office locations. From this we can derive statistics on the usage of the charging stations, including the charging probability, the charging location types and driver behaviours. These results supply accurate and detailed EV driving patterns that are useful for EV charging grid modeling [1].

The WA Electric Vehicle Trial was led and coordinated by local company CO2Smart in cooperation with the Renewable Energy Vehicle Project (REV) at The University of Western Australia (UWA). Some preliminary trial results from this trial have been published in Refs. [32,2].

The majority of EV charging stations were installed as part of an ARC Linkage Project at UWA, while WA Electric Vehicle Trial participants funded the remaining stations. In total there are 23 charging stations installed at twelve different locations (see Fig. 2).

EVs have zero emissions from driving if the electricity supplied is generated from renewable resources. In Australia, the concern about greenhouse gas (GHG) emissions from electricity production has seen a greater desire for energy efficiency and alternative, renewable energy resources [3]. 91.8% of the electricity supplied in Australia is generated from fossil fuels, with the remainder being generated from bioenergy, wind, hydroelectricity and solar photovoltaic (PV) systems [4]. The electricity mix used to charge an EV has a huge impact on its total GHG emissions during the vehicle's lifetime [5]. The domination of fossil fuels in the Australian market significantly increases GHG emissions from the EVs and encourages a focus on maximising the utilisation of renewable energy sources.

To maximise the usage of renewable energy in charging, strategies such as smart charging are being developed [6]. Smart charging is defined as either the EV, the charging station, or the network operator controlling when an EV will charge and how much power the EV should draw at a given time. For an intermittent source of energy such as wind power, smart charging can improve the renewable energy utilisation and therefore reduce GHG emissions [7,8]. Smart charging can also maximise the usage of PV systems, charging the vehicle when the PV system is generating excess power [9]. Smart charging has the downside of additional cost and complexity and requires communication between multiple stakeholders including the energy generator and the EV [10]. However, smart charging offers a huge opportunity to avoid grid overload by deferring charging operations for a large number of EVs [11]. Such systems need to be regulated and standardized to increase safety and performance [12].

Li and Wang [1] provide an overview of modelling plug in hybrid EVs (PHEVs) impact on the distribution grid, suggesting driving patterns, charging characteristics, charge timing, and vehicle penetration are the key factors behind EV energy usage. Some studies simulate EV charging patterns from vehicle fleet patterns [13–15] and will be used for comparison with our results collected. Ashtari, Bibeau [16] use vehicle tracking devices in 76 petrol vehicles and a stochastic method to determine hypothetical charging patterns, creating a load graph by hour. Their results show a charging load profile that has a peak at night when the vehicles are returned home.

Vehicle-to-grid technologies allow the EV to return stored energy into the electricity grid [17]. Research from our group has shown the vehicle-to-grid technologies are not viable due to excessive battery wear and high infrastructural costs [18]. The lifetime of EV batteries is determined by the total number of charge/discharge cycles, so vehicle-to-grid technologies will effectively reduce the life of an EV battery by half [19] and manufacturers such as BMW have opted against using vehicle-to-grid technologies because of this [20]. The charging station infrastructure and the EVs in this trial were not enabled for vehicle-to-grid technologies for the same reasons.

EVs are likely to have a slow uptake [21,22] and it is unlikely EV charging will create significant problems for the WA electrical grid over the next 10 years [23]. Simulation models done for Victoria,


**Fig. 1.** Electric Ford Focus fleet.

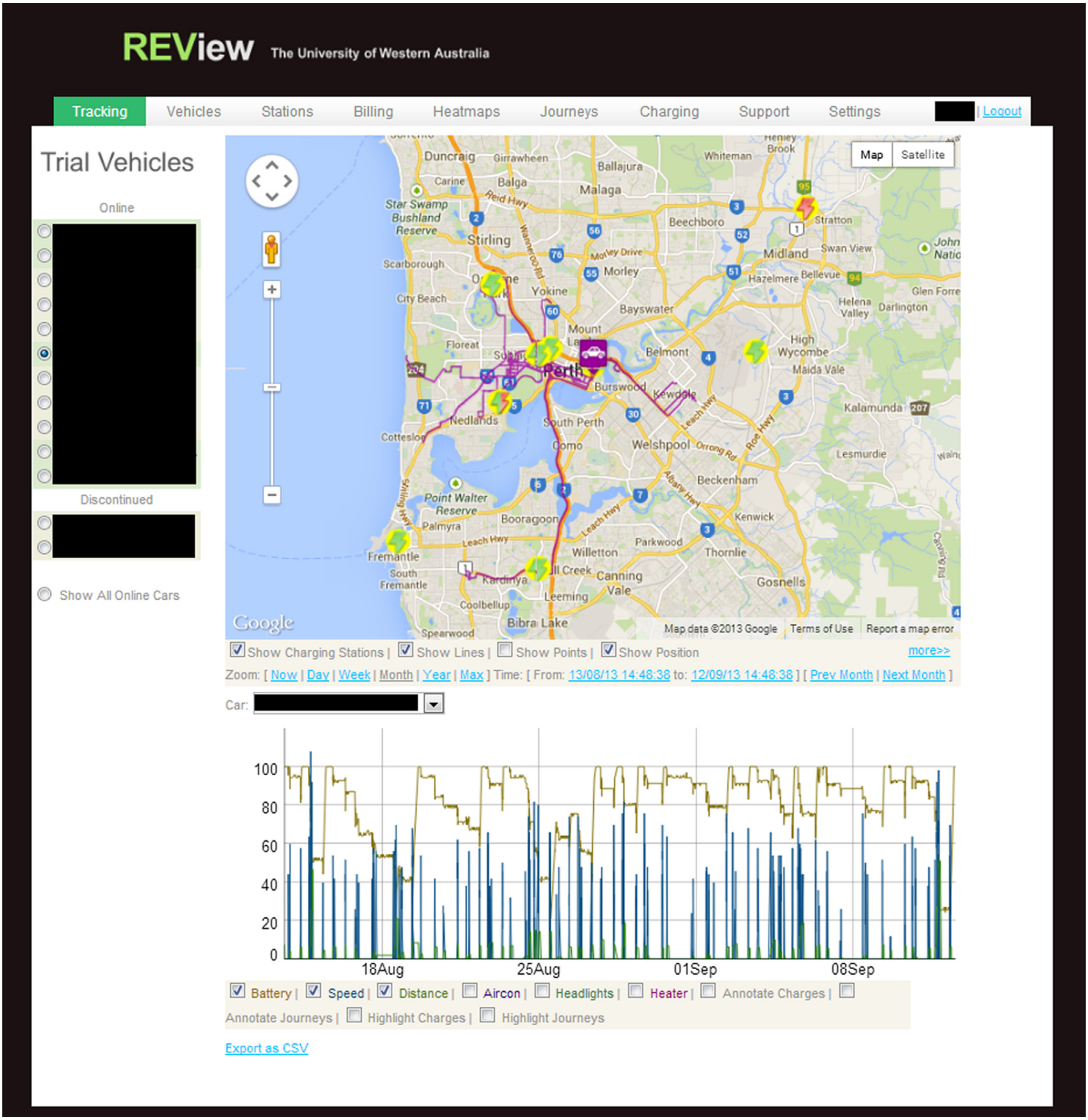


**Fig. 2.** Electric vehicle charging stations installed in Western Australia as part of The University of Western Australia Charging Station trial, shown inside the web software for the EV Trial users.

Australia, predict that a high uptake of EVs of around 15–20% of total non-commercial private motor vehicles by 2030 would increase electricity consumption by only 5% [24]. Even in the unlikely event that there is a large uptake of EVs, the impact on the grid will not be a problem in the short to medium term [22].

## 2. Methodology

### 2.1. EV conversion

A Ford Focus sedan (model year 2010) was chosen as the base vehicle for the WA Electric Vehicle Trial. Eleven vehicles, one for each trial participant, have been purchased and converted to EVs by local company EV Works. The cost to convert the vehicle from petrol to electric was AUD 30,000 (AUD 20,000 in parts and AUD 10,000 in labour) while the original petrol vehicle cost AUD 20,000.

The electric Ford Focus used 45 Thunder Sky Lithium Ion Phosphate batteries in series, each providing 160 Ah at 3.2 V for a vehicle voltage of 144 V and total battery capacity of 23 kWh. This gave the vehicles a maximum driving range of 131 km (road tested) and 143 km (dynamometer tested), respectively, at the date of conversion. The vehicles used a Netgain Impulse 9 motor with an EVNetics Soliton-1 motor controller which was electronically limited to 480 A,

69 kW power output. An electric vacuum pump was fitted for the brake assist and the air conditioning unit was powered by either a separate dedicated electric motor or a belt connection to the vehicle's drive motor.

All of the original 12 V electronics were retained during conversion with an Iota DLS-55 DC-DC converter to charge the 12 V battery from the main battery pack. This included the vehicle's onboard computer, which was required to drive the dashboard instruments, indicators, etc.

The electric Ford Focus was fitted with a Protech 5 kW dual mode battery charger. The charger allows both single-phase charging (low or high current) and three-phase charging. The charger has two modes, one for charging at a three-phase outlet at 4.8 kW and another for a single-phase outlet at 1.8 kW. The vehicle's charger is able to charge the car from empty to full in about four hours at 4.8 kW and about eleven hours at 1.8 kW.

EV chargers draw a consistent and high current for a long time. When the vehicle battery is full, the charger switches to a maintain-charge mode, which maintains the batteries at full charge. The trial EV chargers use on average 120 W to maintain the batteries at full charge.

The vehicle transmission was retained from the original vehicle. Each organisation had a choice of a manual gearbox with or without a clutch or an automatic. Most participants opted for the manual gearbox with a clutch, only the first prototype car was built as a clutchless manual and only one automatic version was built. Both had some significant disadvantages. The clutchless manual has been a standard for many EV conversions and is legally considered an 'automatic' by Australian law. This fact makes it attractive as a pool car for larger organisations, as a significant number of drivers in Australia have automatic-only driver licences. Unfortunately, performing a gear change while driving is required when changing from city driving to freeway driving and back and it is not trivial, especially for inexperienced drivers to change gears without a clutch.

The problem with the automatic gearbox conversions was that at the time of conversion it was not possible to modify the car computer settings to enable smooth gear changes for the electric motor. When taking off, the vehicle would shift quickly between first and second gear as the electric motor quickly gained speed, causing the vehicle to jerk. Therefore the automatic gearbox was locked in third gear when in drive mode. For an automatic transmission the engine is required to be idling at all times, so the electric motors in the trial automatic vehicles would idle at 700 rpm. The locked gear position and the constant idling reduced the road-tested range of the automatic vehicle to around 100 km.

The average EV power consumption with a manual gearbox measured at 197 Wh/km, or 242 Wh/km when including charging losses.

### 2.2. Charging stations and data logging

Level-2 charging stations from manufacturer Elektromotive had been selected for the EV trial and the EV charging research project. Each charging outlet cost AUD3000 to purchase plus an additional AUD1000 for wall mounting or AUD2000 for ground installation. In the absence of an Australian standard, charging stations were purchased complying with the European standard IEC 62196 Type-2 (Mennekes) connectors [25], which unlike the US/Japan standard Type-1 (J1772) does support three-phase charging. Since Australia like Europe does have a three-phase power grid, this should be the obvious choice. Since cables are not a part of Type-2 charging station itself, it can charge both EV types (Type-1 or Type-2) with a matching charge cable.

Each charging station is equipped with a data logger and a GSM modem to transmit charging data to a central host system. On the vehicle side, we have installed GPS-based black box data loggers, which are also equipped with GSM data loggers to transmit vehicle tracking data to our central server. To measure the energy usage of the vehicles, the GPS tracking devices have in addition five digital inputs and one analogue input, which were used to measure the status of the car's air conditioning, heater, headlights, charging, ignition as well as the analogue battery charge level. GPS positions and line inputs are uploaded onto the UWA server either at every minute or at every ten metres, whichever comes first (see Fig. 15). During the duration of the trial 5,640,987 data sets were entered into the database from the eleven EVs (see Fig. 13).

The data is processed using a Python batch script and displayed to the trial participants via a web portal interface (see Fig. 2) that displays telemetry data, driving and charging statistical heat maps for each one of the vehicles. The data processing generates journey, charge and parking events. From the collected GPS data a heat map displaying the EV charging is shown in Fig. 5, EV parking in Fig. 6, and EV movement in Fig. 14.

### 2.3. Charging events and data interpretation

EV driving events are divided into 'journey' segments by the tracking device. Each journey has a start time and location, an end time and location, a total travel distance, air conditioning usage time, heater usage time, headlight usage time and the estimated battery level. A journey starts when the ignition is turned on and ends when the ignition is turned off.

Charging events transmitted from en EV have a start time, end time, location, distance travelled (between charges), energy used (kWh), time charging and time-maintaining charge. A charge event starts when the vehicle's charging hatch (repurposed fuel hatch) is opened and ends when the charging hatch is closed. When an EV is stationary with ignition off and not charging, a parking event is created instead.

Charging stations require the user to identify himself/herself using an RFID tag before charging can commence. The station then logs customer IDs, start time, end time, as well as the amount of energy used for billing purposes. The charging station data is transmitted via GSM to an external server every four hours, from which a batch process downloads the data into the UWA server. The external server is checked every thirty minutes (see Fig. 15). Fig. 16 shows the energy drawn from a charging station from energy metre readings (solid) versus an estimated (ideal) charging profile (dotted).

The GPS tracking units can only log when they have a GPS fix, which usually requires unobstructed view of the sky for the GPS antenna [26]. Throughout the trial, vehicles were parked on occasions within heavy indoor areas, such as parking structures or underground, and have been charged without an active GPS fix. When vehicles have a gap in their data logging of greater than 15 min and have a battery level increase of more than 10%, a charge event is created for the duration of the data loss. In those cases, the charge event is created by estimation using the time the GPS signal was lost to the time the GPS was re-established as the start and end times. If a vehicle loses its GPS fix while driving, the distance between the point before GPS loss and the point of GPS re-establishment is taken to be the distance travelled during the period.

Over the length of the trial 73% (2256–3096) of the recorded EV recharging events occurred at 32 locations with a determined maximum power of 2.4 kW, 3.6 kW or 7.7 kW (10, 15 and 32 A sockets/stations at 240 V). When charging at 10 or 15 A sockets, the vehicles will draw 1.8 kW, while at 32 A sockets (charging stations), vehicles will draw only 4.8 kW, due to limitations in the in-vehicle chargers. The vehicles' charge currents were deliberately reduced on an 10 A outlet for safety reasons, as audits

showed 20% of Australian households having serious electrical safety faults [27] and out of fear of damage to ordinary household power outlets when used for EV charging on a continuing basis.

Consequently, each location was categorised within GPS accuracy as either:

1. Home, at a EV users residence.
2. Business, at places of business such as work, but not at a charging station.
3. Stations, at one of the installed charging stations.
4. Other (unknown location).

## 3. Driving statistics

All EVs in the WA EV Trial are company fleet vehicles and some organisations have placed restrictions on their use, such as not allowing to take the vehicle home. This meant some of the EVs were only used throughout office hours. Also most vehicles were left idle on weekends. Some EVs had dedicated drivers, whilst others were shared pool vehicles with multiple drivers. Although the EVs used in the trial were similar to petrol vehicles, they were still a new technology and required some driver training on charge, range restrictions, etc. Most EV drivers were not reimbursed for electricity usage in their homes and did not have to pay for electricity used at work, which encouraged them to charge at work or at a charging system, rather than at home. These factors are described for each trial vehicle in Table 7.

Table 1 shows average distance, daily distance and distance between charges for each trial vehicle. In 2010 the average distance a passenger vehicle travelled for business in Western Australia was 11,700 km per year or 32.0 km per day [28]. The overall average for the trial over the length of the trial was 22.3 km per day, about two-thirds the West Australian average. The difference between the EV average and the West Australian average was caused by several factors:

- The vehicles were fleet cars, meaning that they would remain idle until they were needed and not be used as often as single user vehicles.
- Possible range anxiety meant that drivers would aim to take shorter trips, or when longer trips were required would take an ICE vehicle from the fleet.
- New users would require training generating smaller journeys that were not actual trips but simply an introduction to the vehicles.
- Some vehicles were used much more often than others because of poor perception of the technology in some companies or poor advertisement of its availability.
- Weekend days are counted but contribute very little of the total distance. Only 9% of the total distance travelled was on weekends but they account for 29% of the total time.

Over the trial period the EVs averaged 2.6 journeys per day. The annual energy usage is 1.55 MWh per EV for driving 22.3 km per. As for ancillary devices, we found that the air conditioner is turned on for 33% of the time, the lights 16% and the heater 3% of the time while driving.

Fig. 3 shows the distance travelled by time-of-day, with 91.31% of the total distance travelled occurring between 7 am and 7 pm. The peaks of distance travelled are at 7 am and 5 pm where vehicle 10 (which contributed 35% of the total kilometres driven)

**Table 1**
EV journeys.

| EV | Number of journeys | Average journey time (min) | Average journey distance (km) | Daily distance (km) | Distance between charges (km) |
|---|---|---|---|---|---|
| 1 | 462 | 19.2 | 9.22 | 29.02 | 16.91 |
| 2 | 430 | 19.63 | 9.59 | 13.82 | 41.19 |
| 3 | 1121 | 13.56 | 7.77 | 21.71 | 21.12 |
| 4 | 339 | 22.16 | 13.46 | 11.9 | 21.46 |
| 5 | 1151 | 11 | 5.29 | 15.64 | 19.48 |
| 6 | 782 | 14.32 | 5.36 | 29.56 | 30.83 |
| 7 | 250 | 12.22 | 5.43 | 8.01 | 17.11 |
| 8 | 856 | 16.39 | 7.35 | 18.69 | 47.85 |
| 9 | 201 | 18.43 | 7.14 | 26.61 | 10.66 |
| 10 | 2180 | 21.31 | 12.23 | 50.86 | 40.23 |
| 11 | 1088 | 15.05 | 7.86 | 14.9 | 13.63 |
| Avg. | 805 | 16.65 | 8.6 | 22.3 | 24.86 |

Journeys accumulated over trial period years.

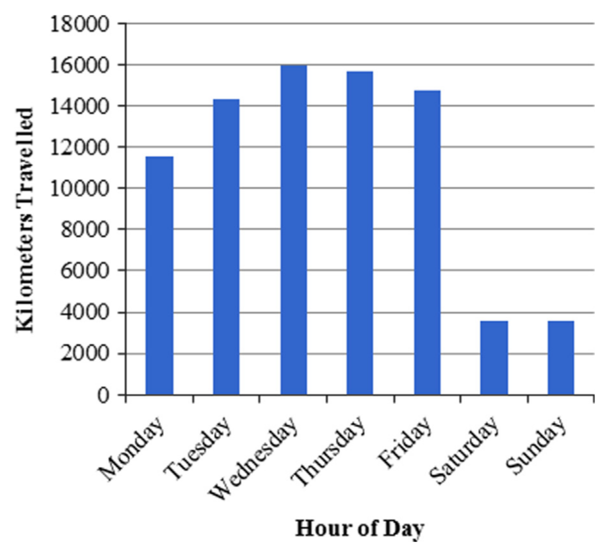


**Fig. 4.** EV travel distance by day of week for each of the 11 vehicles.

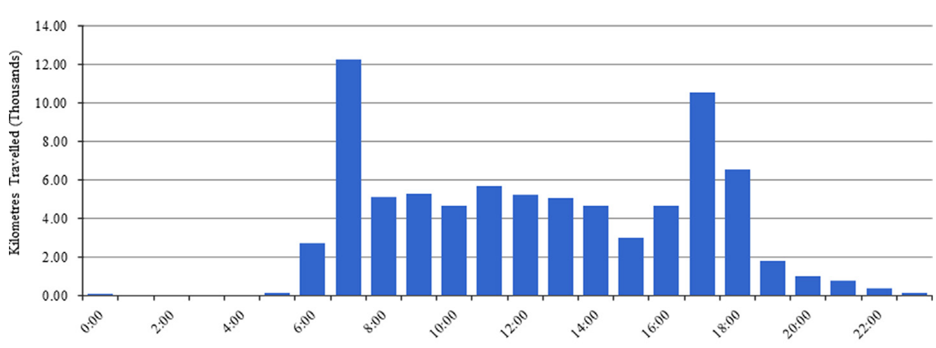


**Fig. 3.** EV travel distance by time of day for each of the 11 vehicles (1–11).

arrives at and leaves from work. About half (48.42%) of the total distance travelled is undertaken between the hours of 9 am–5 pm. The vehicles travelled 90.93% of their total distance on weekdays, with most vehicles not being used on weekends (see Fig. 4).

The kilometres travelled by time-of-day also outline the times when the vehicle needs to have a full charge. EV charging can be delayed or have its power level modified as long as the vehicle has a full battery by 6 am. Knowing this allows a smart charging station to better utilise renewable energy and/or take advantage of time-of-use energy tariffs (such as off-peak and on-peak pricing plans [29]).

## 4. Charging statistics

The number of charging events recorded over the duration of the trial is 2917, with 611 (20.95%) charges not charging to full. The charges are made up of 390 home charges, 963 station charges, 1189 business charges and 375 charges in unknown locations. In these locations 1339 charge events occurred at a high-powered outlet (Level-2: 32 A) and 1203 at low-power outlets (Level-1: 10 A or 15 A) with 375 at an unknown location and socket. Of the number of charges that were stopped before the vehicle was fully charged, 69 occurred at high-powered outlets (13% of all high-powered charges), 141 occurred at low-power outlets (24% of all low-powered charges) and 26 occurred at an unknown location (34% of all unknown charges) (Figs 5 and 6).

The charging statistics shown in Table 2 show the average charging time for EVs at a higher-powered socket is 1 h 25 min and at a lower-powered 10 A socket the vehicles are charged in 2 h 43 min. After the vehicles are charged they remain plugged into the socket for 16 h 20 min on average. Of the total time parked only 10.57% is spent for charging. In Table 3 we show, on average, the EVs were not being driven for 96.15% of the time, or 23 h 4 min per day.

Table 4 shows the parking percentages and charging probabilities in known locations (home, work, or station) versus unknown locations. If multiple staff members got to take the car home and charged it there, some of the 'home charging' events may have shifted to 'elsewhere charging'.

Table 5 shows the probability of charging when parked at a location registered as home, work, station or unknown. The probability of charging is based on the number of parking events at a location versus the total number of charging events. EVs driven and parked at the drivers' homes were recharged only 31% of the 1011 times parked. EVs at the various known business locations were recharged 60% of the 1765 times parked and those parking at charging stations charged 88% of the 1015 times parked. EVs were parked at 5058 different unknown locations and charged at those locations 7% of the times parked. On average 78% of an EV's total parking time occurred in 10 different known locations and on average 90% of recharging time occurred in seven different known locations.

Table 6 shows that for all the EVs in the trial, 89% of charges took place in each EV's top three locations, with on average 82% of charging taking place in the top two locations for each EV.

### 4.1. Charging power

The power (kilowatts) drawn by the trial EVs over time-of-day are shown in Fig. 7. The station and business charging power peaks as the EVs return to work, which were taken home the night

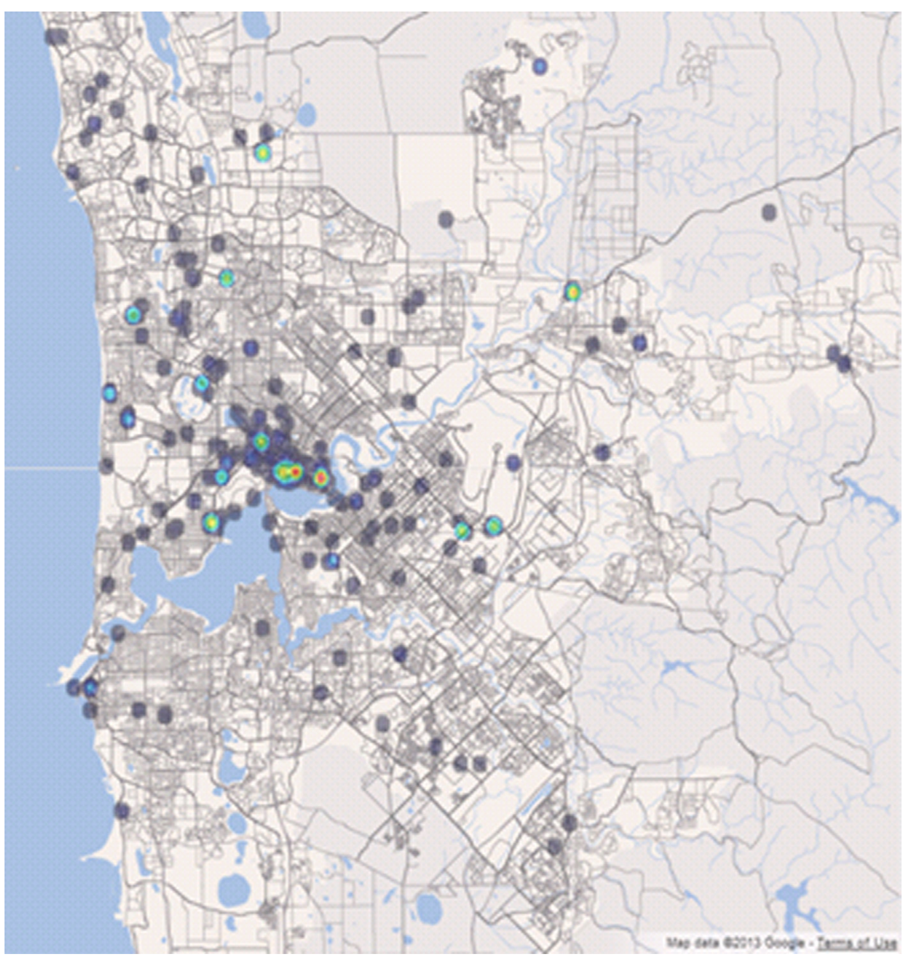


**Fig. 5.** Charging locations for the trial electric vehicles.

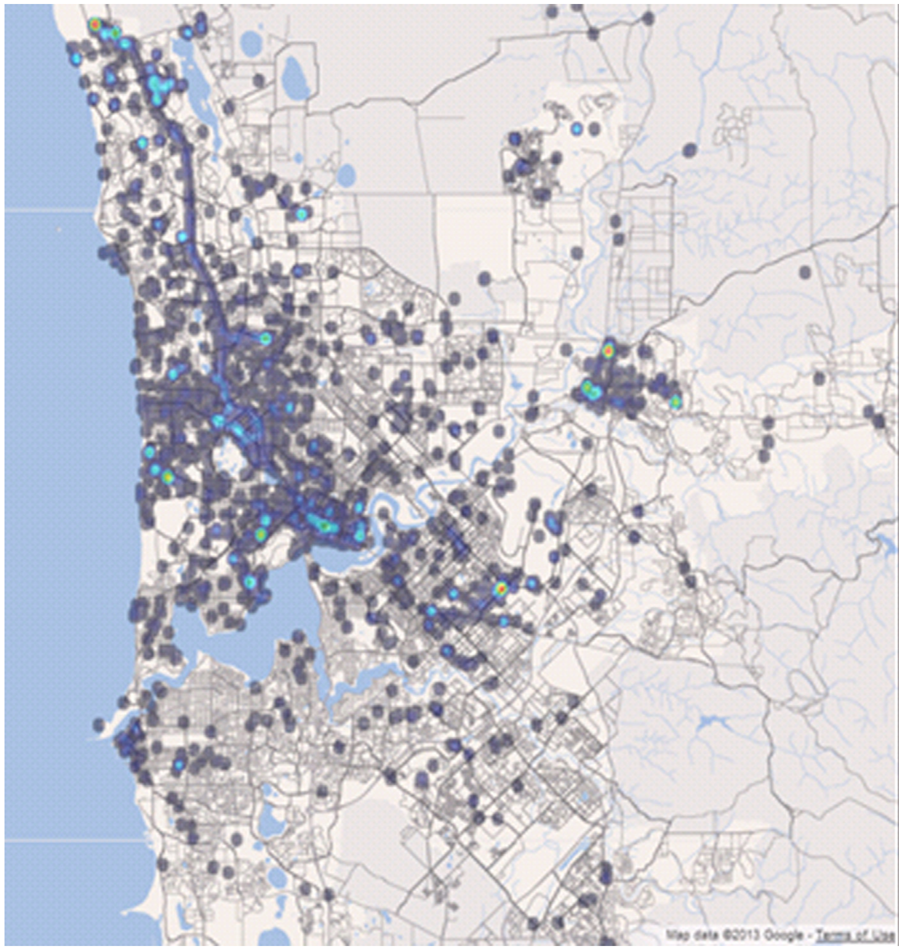


**Fig. 6.** Parking locations for the trial electric vehicles.

**Table 2**
Average energy and duration of charging.

| EV | Avg. kWh | Average charging time | Average maintaining time | Charges at 10, 15 A | Charges at 32 A outlet | Charge time 10 A | Charge time 32 A |
|---|---|---|---|---|---|---|---|
| 1 | 4.01 | 1:44:42 | 35:33:06 | 150 | 17 | 2:06:17 | 0:46:44 |
| 2 | 9.93 | 2:08:22 | 31:06:23 | 3 | 70 | 1:35:22 | 2:15:30 |
| 3 | 6.11 | 1:46:57 | 2:52:04 | 163 | 215 | 2:31:59 | 1:11:41 |
| 4 | 8.13 | 1:11:05 | 38:10:30 | 27 | 160 | 0:14:44 | 1:17:06 |
| 5 | 5.71 | 1:08:01 | 4:52:29 | 92 | 204 | 0:18:56 | 1:26:49 |
| 6 | 8.52 | 3:55:40 | 29:00:49 | 119 | 0 | 4:25:46 | None |
| 7 | 4.32 | 1:59:14 | 64:21:01 | 69 | 1 | 2:07:48 | 0:13:16 |
| 8 | 13.23 | 6:06:05 | 40:55:38 | 130 | 0 | 6:06:34 | None |
| 9 | 2.4 | 1:06:16 | 55:14:06 | 80 | 1 | 1:19:00 | 0:02:08 |
| 10 | 8.69 | 2:28:43 | 6:27:51 | 295 | 301 | 2:53:19 | 1:55:16 |
| 11 | 4.49 | 0:59:31 | 4:42:37 | 75 | 370 | 1:00:59 | 1:02:15 |
| Avg. | 6.62 | 1:55:52 | 16:20:13 | 109 | 122 | 2:43:09 | 1:24:45 |

Number of charge events, the amount of energy supplied and the charging time.

**Table 3**
Vehicle time usage.

| EV | Logged time (h) | Driving time per day (min) | Time driving (%) |
|---|---|---|---|
| 1 | 3524 | 1:00:25 | 4.25 |
| 2 | 7163 | 0:28:17 | 7.35 |
| 3 | 9631 | 0:37:52 | 4.32 |
| 4 | 9206 | 0:19:35 | 1.65 |
| 5 | 9336 | 0:32:32 | 2.00 |
| 6 | 3401 | 1:19:03 | 5.20 |
| 7 | 4067 | 0:18:02 | 4.08 |
| 8 | 8076 | 0:41:41 | 2.91 |
| 9 | 1294 | 1:08:41 | 4.33 |
| 10 | 12,584 | 1:28:37 | 6.43 |
| 11 | 13,768 | 0:28:33 | 2.04 |
| Avg. | 82,052 | 0:43:09 | 3.85 |

before. At 3 pm business power usage also spikes as the EVs are returned back to the businesses from their daytime trip. At 8 pm the home charging peaks as the vehicles that are driven home start slow charging. The power used slowly reduces throughout the night until the next morning.

Fig. 8 shows how often EVs travel a certain distance before being charged. In 83% of charge events the EV had travelled less than 60 km. With the maximum range of the vehicle exceeding 130 km, this shows that the usual behaviour of the EV is to travel less than half of the vehicle's maximum range before charging.

### 4.2. Charging station statistics

Fig. 9 shows the energy in kWh used by time-of-day for the duration of the trial. Of the total energy supplied, 26% occurred between 10 am and 12 pm, when the vehicles that were driven home arrive at a charging station to charge. 79% of the energy is

**Table 4**
Vehicle parking dynamics.

| EV | Percentage parking time at known location (%) | Percentage parking time at unknown location (%) | Unique known locations parked | Unique known locations charged at |
|---|---|---|---|---|
| 1 | 79.51 | 20.49 | 19 | 13 |
| 2 | 83.05 | 16.95 | 13 | 4 |
| 3 | 86.08 | 13.92 | 17 | 11 |
| 4 | 84.04 | 15.96 | 11 | 7 |
| 5 | 79.91 | 20.09 | 8 | 7 |
| 6 | 94.81 | 5.19 | 8 | 2 |
| 7 | 96.75 | 3.25 | 9 | 8 |
| 8 | 47.58 | 52.42 | 6 | 2 |
| 9 | 92.22 | 7.78 | 8 | 7 |
| 10 | 82.03 | 17.97 | 11 | 8 |
| 11 | 43.31 | 56.69 | 13 | 9 |
| Avg. | 77.90 | 22.10 | 11 | 7 |

**Table 5**
Charging location type.

| EV | Charging probability ?at home (%) | Charging probability at work (%) | Charging probability at station (%) | Charging probability at unknown (%) |
|---|---|---|---|---|
| 1 | 35.14 | 87.14 | 52.17 | 18.30 |
| 2 | 0.00 | 59.13 | 0.00 | 10.69 |
| 3 | 23.57 | 43.88 | 88.57 | 4.85 |
| 4 | 0.00 | 40.00 | 94.30 | 9.94 |
| 5 | 75.00 | 6.98 | 97.74 | 2.47 |
| 6 | 0.00 | 61.11 | 0.00 | 3.79 |
| 7 | 66.67 | 52.63 | 100.00 | 2.29 |
| 8 | N/A | 96.03 | 0.00 | 0.14 |
| 9 | 0.00 | 97.00 | 75.00 | 27.96 |
| 10 | 34.35 | 83.97 | 0.00 | 1.79 |
| 11 | 37.50 | 50.00 | 88.71 | 23.20 |
| Avg. | 30.86 | 60.11 | 87.59 | 6.80 |

**Table 6**
Common charging locations.

| | 1 (%) | 2 (%) | 3 (%) | 4 (%) | 5 (%) | 6 (%) | 7 (%) | 8 (%) | 9 (%) | 10 (%) | 11 (%) | Avg. (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Loc. 1 | 52 | 83 | 38 | 76 | 66 | 88 | 51 | 99 | 66 | 49 | 59 | 59 |
| Loc. 2 | 23 | 13 | 15 | 10 | 18 | 12 | 27 | 1 | 24 | 34 | 29 | 23 |
| Loc. 3 | 6 | 2 | 15 | 9 | 6 | 0 | 9 | 0 | 4 | 6 | 9 | 7 |
| Total | 80 | 99 | 68 | 95 | 90 | 100 | 87 | 100 | 93 | 89 | 97 | 89 |

Percentage of total charging energy (kWh) provided by top three used stations for each EV (accumulated over two years, each EV has different locations).

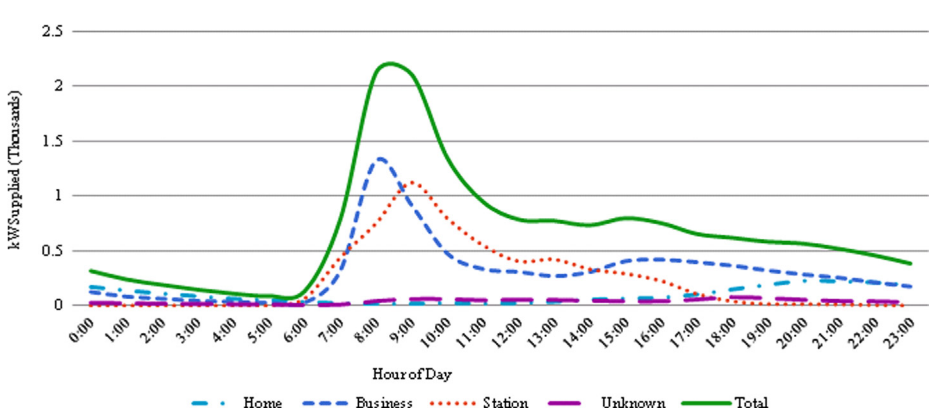


**Fig. 7.** Energy supplied at time of day.

used during daytime, between 8 am and 6 pm. This is during the times that solar PV panels generate power, which means charging stations are an ideal candidate for solar power offset.

When the vehicles are not charging they are maintaining charge, which consumes 24% of the total energy. It is important to note that maintaining energy usage is over the entire length of

the trial and represents the energy needed to maintain the battery at full. This is effectively energy wasted, as it is not used to drive the vehicles, although it could be reduced substantially by configuring the vehicle chargers differently—e.g. to switch off until the battery charge level is degraded by more than 5%.

Fig. 10 denotes how the EVs are spending their time at a charging station. Charging stations were often occupied for a full work day, whilst only charging for a couple of hours. Only 8% of the time parked at a charging station was used to actually charge the EV whilst the other 92% was maintaining the vehicles' charge. The vehicles were completely charged during the maintaining time, only spending a small amount of their total parked time uncharged. This is over the length of the trial including the days when the vehicles were left idle at the charging stations, such as weekends and holidays.

During the length of the trial the charging stations that were most utilised were those located at or near an organisation that had an EV. The small number of EVs participating in the trial (including other private EV owners who had access to the stations) meant that the other stations were rarely used. The combination of this fact and the common charging locations (see Table 6) allows us to conclude that Level-2 charging stations are not necessary where EVs are not commonly parking. Charging usually happens in only one or two locations for each vehicle. These findings reflect on the necessity for high powered DC-charging stations, which were not available for this trial.

### 4.3. Energy tariffs

Fig. 11 shows the amount of energy used and the cost associated with a tariff and the flat-pricing plan, which were available at the time of the trial from the Western Australian electricity retailer Synergy. The tariff used a peak, off-peak, and shoulder segment, where the price for electricity changed depending on the time of day and season. The cost of electricity during an off-peak period is 11.32 cents/kWh, peak is 42.15 cents/kWh and shoulder is 21.44 cents/kWh. The winter months in Australia are April–September, while summer months are October–March.

Fig. 12 shows the total energy used at charging stations over the length of the trial divided up into the different tariff plan pricings. The diagram shows a very large proportion (47%) of charging station EV charging took place within peak times and a very small proportion (6%) during off-peak times. The total cost when charging vehicles at charging stations using a tariff plan would have been AUD2221, which is significantly more when compared to flat-tariff pricing of 21.87 cents/kWh costing AUD1626. As the trial did not use incentives for the EV users to charge at certain times and no method of smart charging was available to the trial participants, the results do not reflect user-controlled pricing (where the EV driver knows and pays for the electricity), but rather a station owner perspective. The trial showed that without smart charging or user incentives, the available time-of-use tariff plan would have been be more expensive than the available flat-rate tariff for EV charging stations.

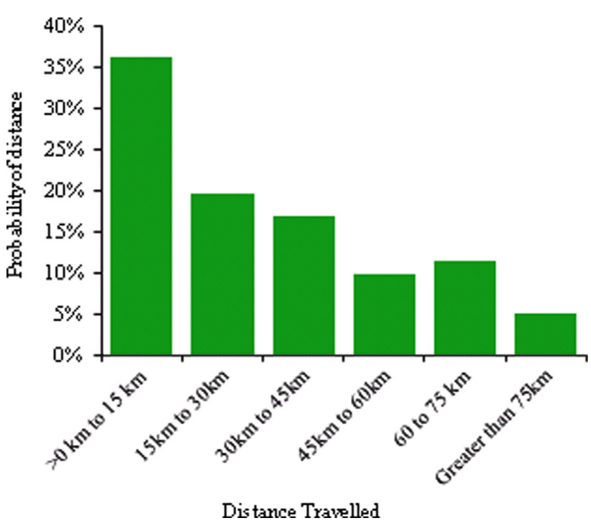


**Fig. 8.** The probability of travelling a certain distance before charging.

## 5. Related studies

### 5.1. Victorian EV trial

The Victorian EV trial with 42 EVs is currently underway in Melbourne, Australia using 14 Mitsubishi iMiEV, 16 Nissan Leaf, seven converted Holden Commodore, and five Blade Electron fully electric vehicles. It has released an interim report that contains some limited statistics [30]. Because there were various issues with data collection and transmission from the vehicles, the interim trial report only includes statistics on the daily distance driven and distance between charge events for the Leaf and the iMiEV EVs. The iMiEV travelled an average distance of 24.5 km per day and the Leaf travelled 32.8 km per day, which is more than the average of the WA EV Trial at 22.3 km. The distance between charge events was 34.3 km and 35.9 km for the iMiEV and Leaf, respectively, which is much longer than the 24.9 km that the Ford Focus averaged in the WA EC Trial. The difference in these values may be attributed to two major differences between the WA and Victorian EV trials:

1. The Victorian trial combines both fleet and household vehicles usage, while the WA trial was solely based on fleet vehicles (with some vehicles allowed to be taken home).
2. Driver confidence may be higher in the OEM-manufactured (original equipment manufacturer) cars of the Victorian trial than the after-market converted Ford Focus in the WA trial.

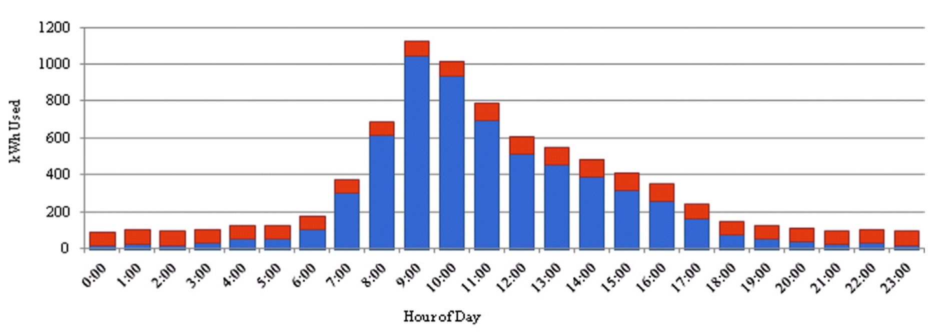


**Fig. 9.** Energy used charging and maintaining over hour of day for the length of the trial.

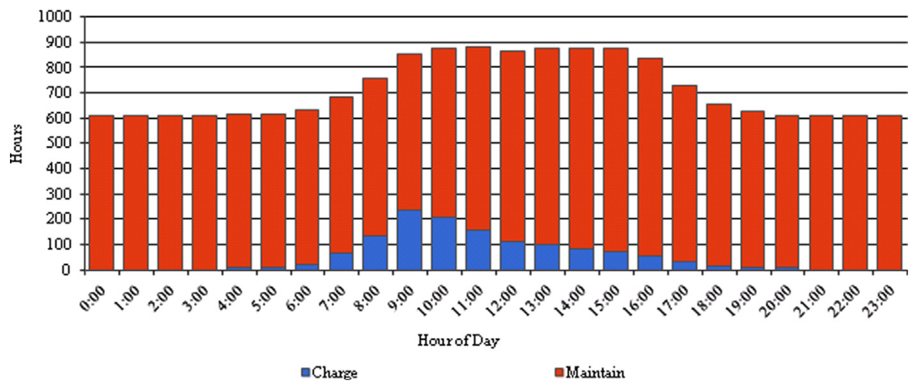


**Fig. 10.** Hours spent charging and maintaining charge over hour of day for the length of the trial.

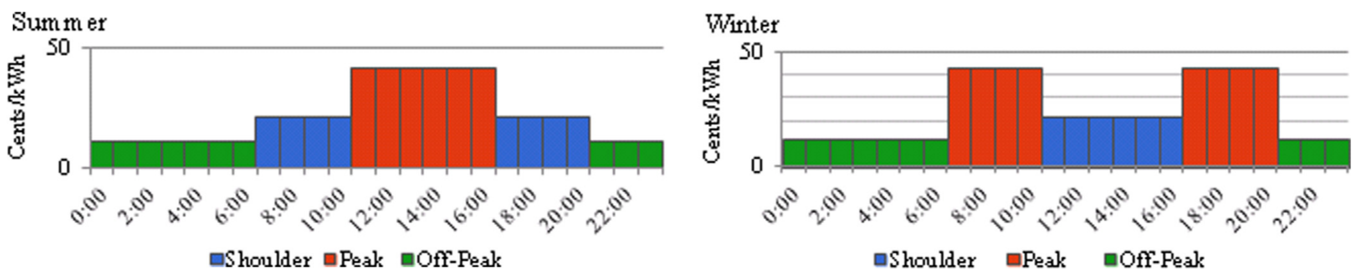


**Fig. 11.** Peak, Off-peak, Shoulder pricing tariff.

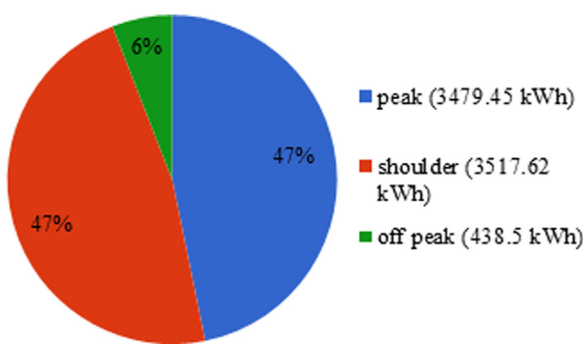


**Fig. 12.** Peak, shoulder, off-peak energy usage over the length of the trial.

### 5.2. Switch EV trial

The Switch EV Trial was conducted in North-East England from 2010–2012. It involved 45 EVs, 20 Nissan Leaf, 15 Peugeot iOns, eleven Avid CUE-Vs, two Liberty E-Range Range Rovers and one Smith Electric Vehicles Edison Minibus. The Switch EV Trial leased the vehicles to a mixture of organisations, councils, car clubs and individuals while tracking their usage. The trial participants were a mix of private drivers, individuals at an organisation and fleet vehicles. Some statistics from this trial is published in Ref. [31].

Similar to the analysis from the WA EV Trial, the Switch EV Trial charging statistics was separated into home, work, public and other locations. There was a peak between 9 am and 10 am when charging at a workplace, while the power curve in the WA EV Trial peaked between 8 am and 9 am (see Fig. 7). However the station charge curve from the WA EV Trial differs significantly from the public charging curve of the Switch EV Trial. This could be due to the following factors:

1. Location of the charging infrastructure.
   The WA EV Trial station charging relied heavily on the charging stations installed through the ARC Linkage grant, as there were very few other charging stations available. The stations that were utilised the most were located at the workplace of an EV Trial participant who had an Electric Ford Focus (and the power curve is similar to charging at work). The Switch EV Trial has its charging infrastructure distributed in different locations including shopping centres and car parks. For the Switch EV Trial this meant that a greater number of charges occurred during the day as the vehicles were parked at these locations.
2. Numbers of charging locations.
   The Switch EV Trial has a significantly larger number of public charging locations (268 versus eleven in the WA EV Trial). The larger number of Switch EV Trial public charging stations was a result of using existing infrastructure installed by EV charging station companies. As there were no commercial charging stations in WA before the trial, the WA EV Trial had access to fewer charging stations.
3. Charging station power output.
   The Switch EV Trial had a mix of Level 1 and Level 2 charging stations. Level 1 stations output less power and thus the EV will be charging for longer (about three times longer than Level 2). Level 2 stations charge the EVs faster and generate more of a peak. Because of this, a mix of Level 1 and Level 2 stations will generate a flattened, longer power curve. The WA EV Trial only utilised Level 2 stations and charged the EVs quicker. This results in higher charging power and shorter charging times, which results in a higher peak.

The home charging curves for both the WA trial and the Switch trial are very similar with a peak in the evening (between 19:00 and 20:00), although the quantity of home charges in the WA trial is significantly less because of the different configuration of the trials.

- The Switch EV Trial results show the recharging by location as:
- Individual users of fleet vehicles: 45% work, 31% public, 17% home and 7% other.
- Fleet pool vehicles: 38% work, 37% public, 18% home and 7% other.

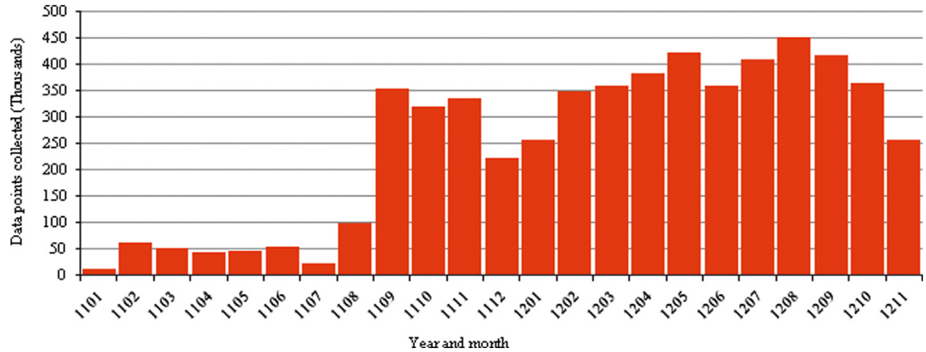


**Fig. 13.** Data collected over time.

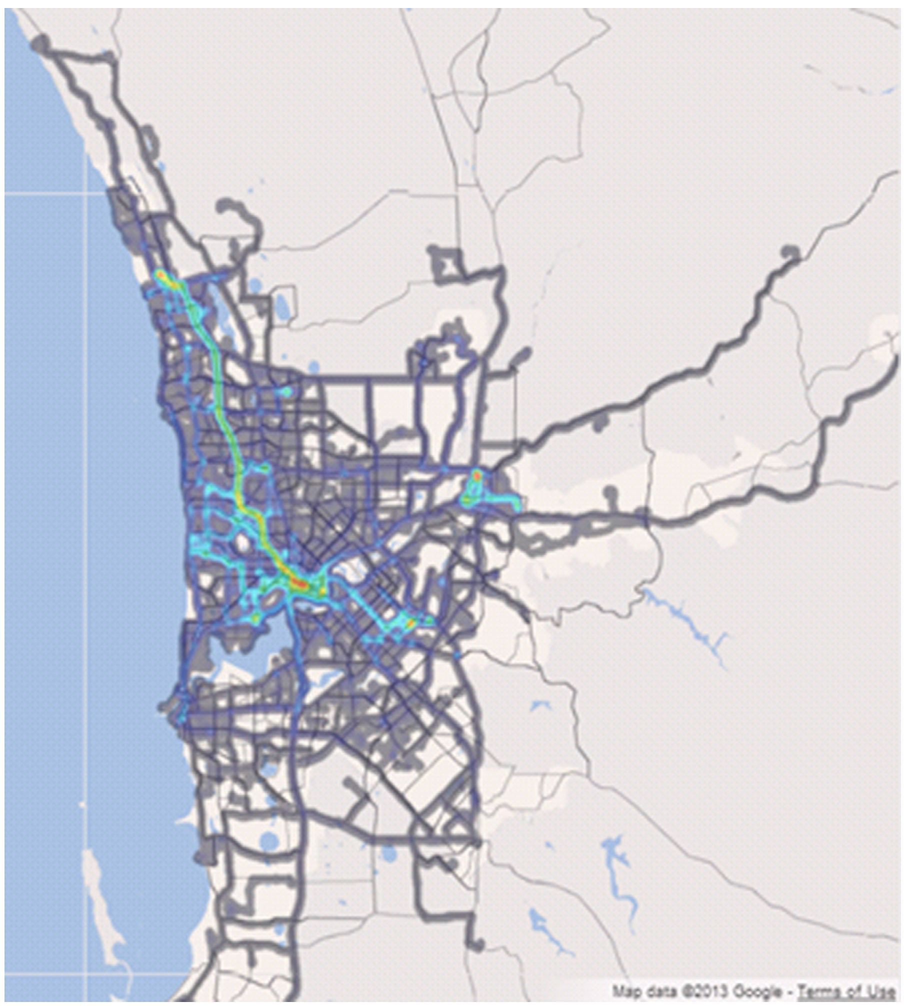


**Fig. 14.** Heat map of the vehicle movement throughout the trial.

- This is quite similar to the results from the WA EV Trial with the EVs charging patterns as:
- 41% work, 33% public (station), 13% home and 13% other (unknown).

The work and public results from the WA EV Trial sit between the individual users and fleet pool results from the Switch EV Trial. This is because the WA EV Trial has individual users and fleet users combined into one group (see Table 7). The bigger difference between the home and other charging results of the two trials is a result of the increased number of "other" locations for the WA EV Trial. A charge occurring at an unknown ('other') location may in fact have been a home location that had not been defined (e.g., multiple home destinations for cars used by multiple drivers).

### 5.3. CSIRO driving statistics

The CSIRO in collaboration with the University of Technology Sydney released a report in 2011 which assesses electric vehicles and their impact on the electricity grid [32]. Using data they obtained from the Department of Transport Victoria, 'Victorian Integrated Survey of Travel and Activity 2007' [33] they generated

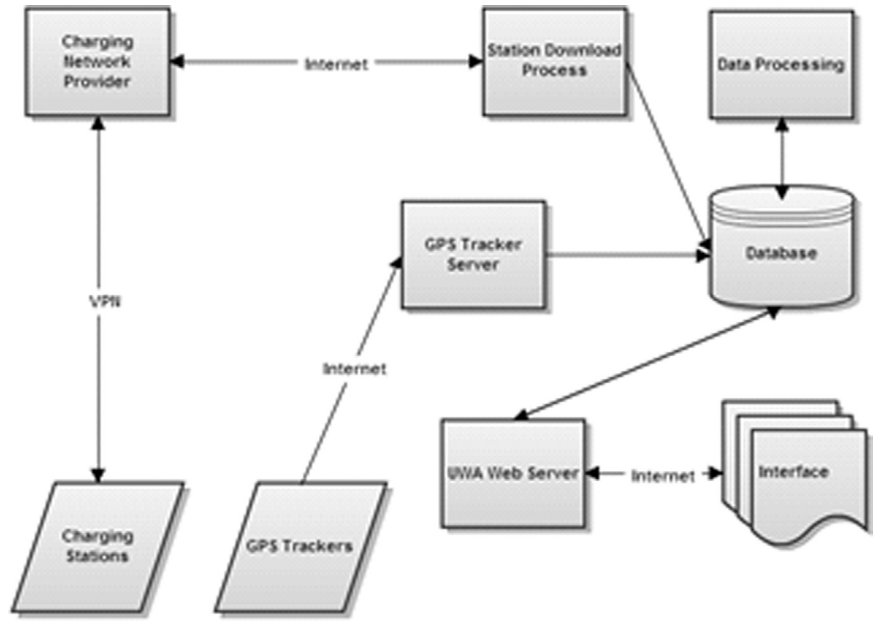


Fig. 15.

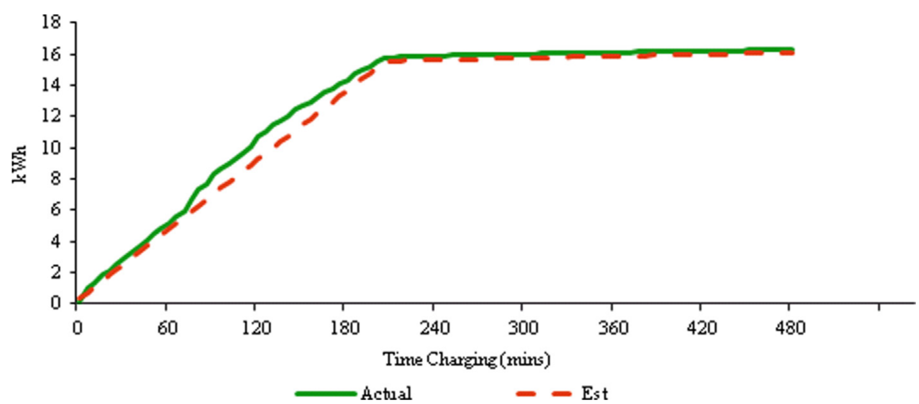


Fig. 16.

**Table 7**
Vehicle details.

| Vehicle number | Single or multiple user | Vehicle take home | Weekend use | Percentage of journeys on weekend (%) | Percentage of distance on weekend (%) |
|---|---|---|---|---|---|
| 1 | Multiple | Yes | Yes | 3.97 | 3.40 |
| 2 | Multiple | Yes | No | 0.00 | 1.54 |
| 3 | Single | Yes | Yes | 14.38 | 14.56 |
| 4 | Multiple | No | Yes | 3.83 | 1.60 |
| 5 | Multiple | No | Yes | 3.83 | 3.76 |
| 6 | Multiple | No | Yes | 4.67 | 5.65 |
| 7 | Multiple | No | No | 0.00 | 0.00 |
| 8 | Multiple | No | No | 0.36 | 1.62 |
| 9 | Multiple | No | No | 0.00 | 0.00 |
| 10 | Single | Yes | Yes | 27.67 | 16.84 |
| 11 | Multiple | Yes | Yes | 5.04 | 3.66 |

Vehicle description table, showing the variations between the different EVs.

a measured kilometres per hour during the week for ICE vehicles in Victoria, Australia. CSIRO used this information to simulate the average energy demand curve for EVs. The results of the Travel Survey for the weekday driving distance per hour are comparable to that of the WA EV Trial (see Fig. 3). The similarity between the two shows that the EVs are being used in a similar manner to ICE vehicles.

However, the CSIRO report's energy demand curve is simulated from the driving distance per hour and therefore does not compare to the power demand curves generated by the WA EV Trial or the Switch EV trial. The CSIRO simulation of power use for charging assumes that the vehicles will distribute their power usage throughout the entire time they are plugged in. This is not the case, as the vehicles can usually charge to full from a daily drive in a few hours on slow charge and about only a third of that time at a Level 2 charging station.

### 5.4. Comparison to simulation studies

Shahidinejad and Filizadeh [34] estimate the probability of charging for a Nissan Leaf and a Chevy (Holden) Volt using computer simulation based on vehicle telemetry data, and conclude a much lower probability of charging than what we found experimentally shown in Table 5. Two possible reasons why the EV drivers charged quite often are the driver's fear of running out of battery or because drivers want the maximum travelable distance available at all times.

The business and station charging patterns are similar to the workplace charge load simulated by Weiller [13]. Possible grid effects (or the lack of it) have been researched in Refs. [23,18].

Axsen and Kurani [35] used a web-based survey as a data set to simulate vehicle charging times, dividing their charging potential into home and workplace. In their simulation when workplace electricity is available they show a similar workplace electricity usage with a peak at between 8 am and 9 am. However, their simulation scenario has the majority of electricity used at home, peaking at 7 pm, whereas our EVs only generated a small energy peak at 4 pm. Kelly and MacDonald [14] developed scenarios from travel surveys to examine the charging times and energy used. They conclude that the peak for most charging will occur at 8 pm, again assuming that the majority of charging occurs at home. Ashtari, Bibeau [16] determine hypothetically that the majority of charging occurs between 6 pm and 7 pm, with a smaller peak in the morning at 7 am, by examining the movements of petrol vehicles. The difference between these studies and our results is likely caused by the influence of free charging at work and the availability of the vehicles outside of work hours.

## 6. Recommendations

The following recommendations are based on the WA Electric Vehicle Trial outcomes. The final report of the trial has been published as Ref. [33].

### 6.1. EV uptake

EV uptake has been quite slow in Australia compared to other countries.

- Some form of short-term government financial support or tax credit would help to kick start the uptake of EVs in Australia.
- With the recent introduction of OEM EVs into the Australian market, an opportunity exists for government organisations to lead by example by including EVs in their fleets. The fleet market will then feed the used car market with EVs in two years' time.

### 6.2. Recharging infrastructure

Level-2 charging stations are misused as free parking bays and occupied for exceedingly long times. It is next to impossible to provide an adequate number of Level-2 charging stations without either EV owners complaining about insufficient charging bays or petrol/diesel car owners complaining about vacant charging/parking bays.

- Small city-wide networks of fast-DC (50 kW) charging stations should be established where the driver will stay with the EV during charging, then move the vehicle.
- There should be no further efforts to extend medium-fast charging (Level-2) or slow-charging (Level-1) networks.
- Demonstration projects such as the proposed ‘Electric Highway’ (Perth to Margaret River) with a chain of charging stations should be funded to link the city to a popular holiday destination and enable EVs to leave the city. This would also have a positive effect on EV uptake.

### 6.3. Standards

Standards Australia has recommended adoption of IEC 62196, but has not recommended either charging connector (Type-1 for single-phase or Type-2 for three-phase).

- A lack of national charging standards is another factor limiting the uptake of EVs.
- Since Australia has a three-phase power grid (like Europe and unlike the U.S./Japan), the obvious choice would be to adopt IEC 62196 Type-2. All OEM EVs support this standard.
- Agreement on national EV standards in Australia will remove a major barrier to the establishment of recharging networks in this country. Failure to prescribe a particular connector/inlet type will lead to the import of cars and charging stations that are incompatible with one another.

### 6.4. Electricity network implications

The introduction of large numbers of EVs and EV charging stations may have significant implications for the management of WA's electricity network, which can be positive (e.g. increased energy revenue) or negative (e.g. higher peak load) for network operators.

- Time-of-use electricity tariffs may be able to ameliorate costs involved with meeting peak network demands and may potentially result in net system benefits.
- More research is needed in intelligent (smart) network protocols, which enable better management of vehicle recharging, and to better understand the potential electricity system impacts of EVs in general.
- Energy utilities, government policy makers and EV industry participants should work collaboratively to maximise the benefits from the introduction of this new transport technology.

## 7. Conclusion

EVs are now starting to appear on our roads, with several major automobile manufacturers producing them. A greater understanding of EV-driver behaviours is important to determine the impact EVs will have. Such an understanding will aid in determining how to power the EVs from renewable resources such as solar and wind power, minimising the GHG emissions. Our findings give evidence showing the effectiveness of installed charging infrastructure with EVs. With that evidence we are able to recommend in what, how and where organisations should invest in to maximise utilisation and minimise cost.

Our results showed that energy used by the vehicles to charge from the grid peaked between 8 am and 10 am as vehicles came into work. Charging stations supplied the most energy to EVs during the day, which could be offset by solar PV systems. Installed charging infrastructure is only consistently utilised when there is an EV daily commuting to and from the station and does not seem economically viable while there is such a low population of EVs. The average distance before charging was well below the maximum range of the vehicles with 83% of charge events occurring when the vehicle still has more than half of its maximum allowable range remaining. Large amount of time spent at charging stations was in maintaining charge (92% of the total time plugged in) not actually charging. This means that the charging stations are not being fully utilised while a vehicle is plugged in.

In the trial Level-2 charging infrastructure was used and was not fully utilised. From the driving patterns of the EVs we can see that the vehicles are usually parked and left charging in only one or two locations (at home or work). The EVs are generally left charging for a long time at these locations and do not require a full charge as they usually have a significant amount of energy left in their batteries. The additional cost for the Level-2 (7.2 kW) stations over the Level-1(2.4 kW) stations is not justified with such long

maintaining charge times (parking without full-power charging) as the Level-1 stations will quite often fully recharge the EV.

From the study's findings we can also make some more involved conclusions. The purchase of level 1 or level 2 charging stations for public usage will not be properly utilised whilst there is still such a low number of EVs who have many other opportunities to recharge. Also in these public networks, the energy supplied from the station is not as utilised as the parking space is, making it difficult to profit off electricity consumption alone. These public networks will be likely installed and maintained to encourage EV usage, without being profitable on their own.

There is room in the market for the installation of a smaller fast-DC charging network in favour of a larger Level-2 AC network which would satisfy EV driver's rare need for a quick full recharge. At fast charging stations EV owners would then have to stay with their cars during the charging process, which would become very similar to the refuelling of a petrol or diesel vehicle.

Level 1 charging stations should still be purchased privately. Organisations which want to reduce their GHG emissions and running costs through the purchase of EVs should invest in charging infrastructure for their vehicle and also install solar PV. The station will be well utilised as it is the primary charging location for an EV (we showed that an average of 60% of charging will occur there). Also, the station also supplies safety, security and logging that allows an organisation to keep track of energy usage. The risks involved in charging an EV make it very important that organisations have the industrial EV charging standard connectors and cables and other electrical safety devices which are built into charging stations. Finally, only a Level 1 charging station is necessary in this circumstance because of the long parking times allowing for slower charging, and reducing the cost of the station. A solar PV system will also be properly utilised, as the power typically supplied to the electric vehicles is throughout the daylight hours.

## Acknowledgements

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## References

[1] Green Ii RC, Wang L, Alam M. The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook. Renew Sustain Energy Rev 2011;15(1):544–53.
[2] Fakhra Jabeen SS, Doina Olaru, David Harries, Thomas Bräunl. Acceptability of electric vehicles: findings from a driver survey. Australian Transport Research Forum; 2012.
[3] Western Power Annual Report; 2011.
[4] Schultz A, Petchey R. Energy update; 2011.
[5] Faria R, Marques P, Moura P, Freire F, Delgado J, de Almeida AT. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew Sustain Energy Rev 2013;24(0):271–87.
[6] Erol-Kantarci, M Mouftah HT. Prediction-based charging of PHEVs from the smart grid with dynamic pricing. In: Proceedings of IEEE 35th Conference on Local Computer Networks (LCN); 2010.
[7] Mets K, De Turck F, Develder C. Distributed smart charging of electric vehicles for balancing wind energy. In: Proceedings of the IEEE Third International Conference on Smart Grid Communications (SmartGridComm); 2012.
[8] Mischinger S, Hennings W, Strunz K. Integration of surplus wind energy by controlled charging of electric vehicles. In: Proceedings of the 3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe); 2012.
[9] Tulpule PJ, Marano V, Yurkovich S, Rizzoni G. Economic and environmental impacts of a PV powered workplace parking garage charging station. Appl Energy 2013;108(0):323–32.
[10] San Román TG, Momber I, Abbad MR, Sánchez Miralles Á. Regulatory framework and business models for charging plug-in electric vehicles: infrastructure, agents, and commercial relationships. Energy Policy 2011;39 (10):6360–75.
[11] Dallinger D, Wietschel M. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. Renew Sustain Energy Rev 2012;16(5):3370–82.
[12] Brown S, Pyke D, Steenhof P. Electric vehicles: the role and importance of standards in an emerging market. Energy Policy 2010;38(7):3797–806.
[13] Weiller C. Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States. Energy Policy 2011;39(6):3766–78.
[14] Kelly JC, MacDonald JS, Keoleian GA. Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Appl Energy 2012;94(0):395–405.
[15] EPRI, Transportation Electrification: A Technology Overview; 2011.
[16] Ashtari A, Bibeau E, Shahidinejad S, Molinski T. PEV Charging Profile Prediction and Analysis Based on Vehicle Usage Data. IEEE Trans Smart Grid 2012;3 (1):341–50.
[17] Srivastava AK, Annabathina B, Kamalasadan S. The challenges and policy options for integrating plug-in hybrid electric vehicle into the electric grid. Electr J 2010;23(3):83–91.
[18] Mullan J, et al. The technical, economic and commercial viability of the vehicle-to-grid concept. Energy Policy 2012;48:394–406.
[19] Richardson DB. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. Renew Sustain Energy Rev 2013;19(0):247–54.
[20] Göthel J, Bräunl T. editor. BMW, E1-33; 2012.
[21] AECOM. Economic Viability of Electric Vehicles; 2009.
[22] Järvinen J, Orton F, Nelson T. Electric vehicles in Australia's national electricity market: energy market and policy implications. Electr J 2012;25(2):63–87.
[23] Mullan J, Harries D, Bräunl T, Whitely S. Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system. Energy Policy 2011;39(7):4349–59.
[24] Gerardi W. Electricity Markets and the Uptake of Electric Vehicles; 2009.
[25] Commission IE. Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles – Part 1: general requirements. Int Electrotech Comm 2011:151.
[26] Kaplan E, Hegarty C. Understanding GPS Principles and Applications: Principles and Applications. Norwood: Artech House Books; 2005.
[27] MEA. Switch Thinking – Preventing Electrical Deaths in Australian Homes; 2011. 〈http://issuu.com/master_electricians/docs/switch_thinking_report?mode=window〉.
[28] ABS. Survey of Motor Vehicle Use, A.B.o. Statistics, editor; 2011.
[29] Kristoffersen TK, Capion K, Meibom P. Optimal charging of electric drive vehicles in a market environment. Appl Energy 2011;88(5):1940–8.
[30] Creating a Market, Victorian Electric Vehicle Trial Mid-Term Report, V.D.o. Transport, editor; 2013.
[31] Robinson AP, Blythe PT, Bell MC, Hübner DY, Hill DGA, Analysis of electric vehicle driver charging behaviour and use of charging infrastructure. In: Proceedings of the 8th World Congress on Intelligent Transport Systems. Vienna, Austria; 2012.
[32] CSIRO. CSIRO electric driveway project plugging. In: A Technical and Institutional Assessment of Electric Vehicles and the Grid in Australia Phase 1 Report; 2011.
[33] Victoria DoT. Victorian Integrated Survey of Travel and Activity 2007, D.o.T. Victoria, editor; 2009.
[34] Shahidinejad S, Filizadeh S, Bibeau E. Profile of charging load on the grid due to plug-in vehicles. IEEE Trans Smart Grid 2012;**3**(1):135–41.
[35] Axsen J, Kurani KS. Anticipating plug-in hybrid vehicle energy impacts in California: Constructing consumer-informed recharge profiles. Transp Res Part D: Transp Environ 2010;15(4):212–9.